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New Correlations for Time Lags and Pressure Response Amplitude in Pulse-Test Analysis

N.A.F. El-Khatib, King Saud U. of Petroleum & Minerals
SPE Member

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ABSTRACT

The equations for pulse test analysis by the tangent construction method are formulated in a general way to account for the possibility of the time lag exceeding the pulse or shut-in periods. The equations are solved for the dimensionless cycle period and response amplitude for a wide range of the relative time lag for the first four cycles and at different pulse ratios between 0.1 and 0.9. Cases with difficulties in solving the equations are discussed and their physical and mathematical interrelations are explored. A single set of correlation curves for the dimensionless cycle period is presented for all cycles while a seperate set of curves for the dimensionless response amplitude for each of the first four cycles is needed. The significance of using correlations for the three time lags is discussed.

INTRODUCTION

Pulse testing is widely used for the estimation of interwell reservoir properties such as porosity and permeability. In a pulse test, the flow rate at the active well is changed periodically between flowing and shut-in while the pressure is monitored at an observation well some distance away[1,2]. The conventional method of pulse test analysis consists of drawing a tangent to the pressure-time curve between two peaks (valleys) and a parallel tangent at the valley (peak) between them. Three time lags and the pressure response amplitude are then determined. Correlation curves developed by Brigham[2] for the equal and by Kamal and Brigham for unequal pulse and shut-in periods are used to estimate the reservoir transmissivity Kh/μ and sotrativity $h\phi C_t$. In these correlation curves, only the middle time lag $t_{\ell m1}$, is used. Recently, Ogbe and Brigham[4] and Al-Khalifah et al[5] found some discrepancies in the original Kamal-Brigham curves and published new correlation curves.

The correlation curves that relate the relative time lag and dimensionless response amplitude to the dimensionless cycle period are obtained by solving the three equations that specify the equality of the slopes of tangents at the three time lags with the slope of the line connecting the two outer points. Expressions for the pressures and pressure derivatives at the different points used in these equations are obtained from the line source solution and the application of the principle of superposition.

When the rate at the acative well is changed from flowing to shut-in or vice versa, a certain time is elapsed before the pressure trend at the observation well is reversed. This is termed the time lag. The equations presented in references (2-5) are correct if the pressure trend is reversed before the conditions at the active well are changed again, i.e. the time lag does not exceed the flow or shut-in period. If the time lag exceeds these periods, the pressure trend is reversed after another change in the flow conditions at the active well occurs. In this case the equations presented in references (2-5) are in error and additional superposition term must be added to the summations[6]. This implies that the correlation curves are only correct for values of the time lag less than the pulse period for even cycles and less than the shut-in period for odd cycles.

The main objective of this work is to develop the correct equations for the entire time lag region and obtain the correlation curves by simultaneous solutions of the correct equations. As was noted before, the previous correlations employ only one of the three time lags, t_{l1}. The use of any of the three time lags would be sufficient if there were no measurement errors in the pressure response at

References and illustrations at end of paper.

the observation well. When such measurement errors exist, as usually the case, the use of any of the time lags would result in different estimates of reservoir properties. The availability of correlations for the three time lags would check for the consistency of the measured data and confirm the reliability of the estimated properties.

THEORY

As shown in Figure 1, the cycle period Δt_{cyc} is divided into two parts, the flow period $R'\Delta t$ and the shut-in period $(1-R')\Delta t$ where R' is the pulse ratio. The flow and shut-in periods are numbered such that flow periods are even starting with zero (0, 2, 4, ...) and the shut-in periods are odd (1, 3, 5...). Any pulse period n lies between times t_{n-1} and t_n where

$$t_n = \begin{cases} \frac{n}{2}\Delta t_{cyc} & (n \text{ even}) \\ \left(\frac{n-1}{2} + R'\right)\Delta t_{cyc} & (n \text{ odd}) \end{cases} \quad (1)$$

For any point t such that $t_n < t < t_{n+1}$, the pressure drop ΔP is given by

$$\Delta P(t) = \frac{-70.6\, q\mu B}{Kh} \sum_{i=0}^{n} (-1)^i E_i\left(\frac{-56900\, S\, r^2}{T(t - t_i)}\right) \quad (2)$$

Using dimensionless variablea as defined in the appendix, Equation (2) takes the form

$$P_D = -\tfrac{1}{2} \sum_{i=0}^{n} (-1)^i E_i\left(-\frac{1}{\Delta t_{cycD}(t_D - t_{Di})}\right) \quad (3)$$

The pressure derivative with respect to the relative time t_D is given by

$$P_D' = \tfrac{1}{2} \sum_{i=0}^{n} (-1)^i \frac{\exp\left(\frac{-1}{\Delta t_{cycD}(t_D - t_{Di})}\right)}{(t_D - t_{Di})} \quad (4)$$

Considering the pulse test analysis by the tangent method for the first pulse period n(even) as shown in Fig.1. A tangent is drawn between points A and C while a parallel tangent is drawn at point B. It is seen that

$$t_{DA} = t_{Dn} + t_{\ell Do} \quad (5)$$
$$t_{DB} = t_{Dn+1} + t_{\ell D1} \quad (6)$$
$$t_{DC} = t_{Dn+2} + t_{\ell D2} \quad (7)$$

Equations (5-7) are used in Eqs. (3) and (4) to evaluate the pressures and pressure derivatives at points A, B and C. Let

$$SE(n,j) = -\tfrac{1}{2} \sum_{i=0}^{n+j} (-1)^i E_i\left(\frac{-1}{\Delta t_{cycD}(t_{Dn} - t_{\ell Dj} - t_{Di})}\right) \quad (8)$$

$$SX(n,j) = \tfrac{1}{2} \sum_{i=0}^{n+j} (-1)^i \frac{\exp\left(\frac{-1}{\Delta t_{cycD}(t_{Dn} - t_{\ell Dj} - t_{Di})}\right)}{(t_{Dn} + t_{\ell Dj} - t_{Di})} \quad (9)$$

$$(j = 0, 1, 2)$$

We can write

$$P_{DA} = SE(n, 0) = E_0 \quad (10)$$
$$P_{DB} = SE(n, 1) = E_1 \quad (11)$$
$$P_{DC} = SE(n, 2) = E_2 \quad (12)$$

and

$$P_{DA}' = SX(n, 0) = X_0 \quad (13)$$
$$P_{DB}' = SX(n, 1) = X_1 \quad (14)$$
$$P_{DC}' = SX(n, 2) = X_2 \quad (15)$$

Although Eqs. (5-7) are correct regardless of the values taken by the time lags, the number of superposition terms in the summation (upper limit) will be changed, if the time lag exceeds the corresponding pulse period. To account for this cases, the term n in Equations (8,9) should be replaced by K such that

For even n

$$K = \begin{cases} n & t_{\ell Dj} \le R' \\ n+1 & R' < t_{\ell Dj} \le 1 \\ n+2 & 1 < t_{\ell Dj} \le 1+R' \\ n+3 & 1+R' < t_{\ell Dj} \le 2 \end{cases} \quad (16)$$

and for odd n

$$K = \begin{cases} n & t_{\ell Dj} \le 1-R' \\ n+1 & 1-R' < t_{\ell Dj} \le 1 \\ n+2 & 1 < t_{\ell Dj} \le 2-R' \\ n+3 & 2-R' < t_{\ell Dj} \le 2 \end{cases} \quad (17)$$

In order for the slopes of tangents at points A, B and C to be equal and also equal to the slope of the line connecting points A and C we must have

$$X_0 = X_1 = X_2 = m \quad (18)$$

$$m = \frac{E_2 - E_0}{1 + t_{\ell D2} - t_{\ell Do}}$$

Equations (18) and (19) represent three nonlinear equations that can be solved for any three of the four variables t_{cycD}, $t_{\ell Do}$, $t_{\ell D1}$ and $t_{\ell D2}$ provided one of the four variables is known and the pulse ratio R' and pulse cycle number n are specified.

The Newton-Raphson iteration method is used to solve the three simultaneous nonlinear equations for $t_{\ell Do}$, $t_{\ell D2}$ and t_{cycD}. After the three equations are solved, the dimensionless response amplitude P_{rD} can be obtained from the equation.

$$P_{rD} = E_i - \{E_o + m[(t_{Dn+1} + t_{\ell D1}) - (t_{Dn} + t_{\ell Do})]\} \quad (20)$$

RESULTS AND DISCUSSION

For a fixed value of the pulse ratio R', solutions were obtained for the first four pulses. The value of the middle relative time lag $t_{\ell D1}$ was varied from 0.05 to 1.0 and the dimensionless cycle period Δt_{cycD}, the response amplitude P_{rD} and the two relative time lags $t_{\ell Do}$ and $t_{\ell D1}$ were obtained from the solution of the three nonlinear equations. Sample results of the program output are shown in Tables 1 - 3.

It was observed that for large values of relative time lag $t_{\ell D1}$ and particularly for pulse ratios close to zero or one, no convergence of the solution was reached. As one may expect, the relative time lag is inversely proportional to the dimensionless cycle period Δt_{cycD}. To examine the behavior of the pressure response at low values of Δt_{cycD}, dimensionless pressure was generated for different values of Δt_{cycD} at a pulse ratio R' of 0.5 using Eq. (2). The results are shown in Fig. 2. It is clear from this figure that at low values of Δt_{cycD} (below 0.5), the pressure response to the pulsating rate is almost unnoticeable with no clear peaks and valleys. The numerical solution tries to find two points with $t_{\ell do}$ and $t_{\ell d1}$ such that the tangents at these two points and the chord connecting them will have a slope equal to that of the tangent at the point $t_{\ell d1}$. When no peaks and valleys are present, the only plausible mathematical solution for the problem is that the three points A, B and C are coincident. In this case

$$t_{\ell do} = \begin{cases} t_{\ell d1} + R' & \text{(even n)} \\ t_{\ell d1} + (1-R') & \text{(odd n)} \end{cases} \tag{21}$$

$$t_{\ell d2} = t_{\ell d1} + 1 \tag{22}$$

$$P_{rD} = 0 \tag{23}$$

If the algorithm does not allow for the points A and C to coincide on point B, the solution will be as close to point B as the program allows. When such behavior is observed, the points are eliminated and are not included in the plots. The last two points in Table 2 are an example such situation.

Figure (3) shows the pressure behavior at a dimensionless cycle period of 1 for different values of the pulse ratio R' ranging from 0.1 to 0.9. It is obvious that a value of R'=0 represents no flow (P_D = 0) and a value of R'=1 represents constant flow rate (line-source solution). Although the absolute value of the pressure increases as R' increases, the pressure response amplitude is the largest for pulse ratios close to 0.5 and decreases as the pulse ratio approaches 1 or zero. However, it is clear from Fig. (3) that for pulse ratios close to zero (0.1 and 0.2) the peaks and valleys in the response curves are more noticeable than in the curves for pulse ratios close to 1 (0.9 and 0.8).

Figures (4) and (5) show the pressure behavior at values of R' of 0.9 and 0.1 respectively for different values of Δt_{cycD}. Investigation of Figure (4) shows the difficulty of drawing a tangent for the first even pulse (n=0) for all the curves. For the other even pulses (n=2,4) it is possible to draw tangents only for curves of $\Delta t_{cycD} > 2$. For odd pulses, it is possible to draw tangents (between peaks) for curves of Δt_{cycD} of 2 or larger. This was reflected in the computer results where no convergence was possible at R'=0.9 for even pulses. Difficulties were also encountered in the convergence of solution at R'=0.1 for odd pulses at small time lags. This may be the result of the sharp change in slope at the peaks for large values of Δt_{cycD} as clear from Fig. (5).

RESULTS FOR DIMENSIONLESS CYCLE PERIOD

At a given pulse ratio R', investigation of the results of Δt_{cycD} vs. $t_{\ell d1}$ shows that the curves for even pulses (n = 0,2) coincide. The same behavior is also noted for the odd pulses (n = 1,3). Furthermore, it was noticed that the curves for even pulses at R' coincide with the curves for odd pulses at (1-R'). At R'=0.5, the curves for even and odd pulses (n = 0,1,2,3) coincide. Such findings are apparent from Figure (6) where the curves for R' of 0.3, 0.5 and 0.7 are shown for even and odd cycles. These conclusions make it possible to use a single set of correlation curves of Δt_{cycD} vs. $t_{\ell d1}$ for even and odd pulses. Figure 7 shows the results obtained for the first even cycle (n=0) at values of R' from 0.1 to 0.8. The curve for R'=0.9 is obtained from the first odd cycle (n=1) at R'=0.1. This figure can be used for both even and odd pulses provided R' for odd pulses is matched by 1-R' for even pulses. Figure 6 shows that the error would be less than 5% for most of the points. Only at R'=0.1 for odd pulses and R'=0.9 for even pulses are the results in doubt. Such situations however are seldomly used in pulse test analysis.

RESULTS FOR DIMENSIONLESS RESPONSE AMPLITUDE

Figure (8) shows the dimensionless response amplitude P_{rD} vs. $t_{\ell d1}$ at pulse ratios of 0.3, 0.5 and 0.7 for even pulses. Investigation of this figure shows that the curves for even pulses (n = 0,2) coincide for values of P_{rD} above 0.01 while the curves start to depart for P_{rD} below this value. Investigation of the results showed a similar behavior for odd pulses. The results also show that curves for the even pulses at R' do not coincide with those for odd pulses at (1-R') even for high values of P_{rD}. It is therefore appropriate to present seperate correlation curves for each of the first four pulses for the dimensionless response amplitude. The curves are shown in Figures (9-12).

RESULTS FOR RELATIVE TIME LAG

The correlation curves for dimensionless cycle period and dimensionless response amplitude were presented as functions of $t_{\ell d1}$, the relative time lag at the middle point B of the pulse period in question. As stated earlier, only in simulated examples would the use of $t_{\ell d1}$ give the correct results. In actual examples however there will be errors in the estimated time lags $t_{\ell o}$, $t_{\ell 1}$ and $t_{\ell 2}$ It is clear from the solutions of the model equations that $t_{\ell do}$ and $t_{\ell d2}$ are functions of $t_{\ell d1}$ and the pulse ratio R' as well as the pulse number n. Brigham assumed that for equal pulse and shut-in periods (R'=0.5), the three time lags are equal. Results from Tables 1 - 3 indicate this to be incorrect for equal as well as unequal pulse and shut-in periods. Figure 13 shows a plot of $t_{\ell Do}$ and $t_{\ell D2}$ as functions of $t_{\ell D1}$ for the first four pulses at R'=0.5. The agreement of the measured and correlated time lags would show the reliability of the measured data and strengthen the confidence in the obtained results. Only correlations of the three time lags for R' = 0.5 is presented here.

ILLUSTRATIVE EXAMPLE

A case is considered where two wells are 500 ft apart. The values of T and S are assumed to be 100 md.ft/cp and 1.98×10^{-6} ft/psi respectively. The flow rate at the active well is 50 res.bbls/day and the total cycle period is 10 hrs with a pulse period of 8 hrs and a shut-in period of 2 hrs. The pressure response is generated and plotted in Figure 14. The tangent construction methods gives the following results.

$t_{\ell 1} = 1$ hr , $t_{\ell d1} = 0.1$, $P_r = 4.67$ psi

From table 3

$P_{rD} = 0.144$, $\Delta t_{cycD} = 2.2766$

$$T = \frac{70.6\, q\, L\, P_{rD}}{P_r}$$

$$= \frac{70.6 \times 50 \times 0.144}{4.67} = 108.85 \text{ md.ft/cp.}$$

$$S = \frac{T \Delta t_{cyc}}{56900\, r^2 \Delta t_{cycD}} \quad \frac{108.85 \times 600}{56900 \times 50 \times 2.2766}$$

$$= 1.0137 \times 10^{-6} \text{ ft/psi}$$

These results indicate an error of 8.85% in the transmissivity T and 1.7% in the Storativity S.

The same example solved by nonlinear regression gave a transmissivity and storativity of 99.627 md.ft/cp and 1.97726×10^{-6} ft/psi respectively (7). The error is less than 0.4% in the transmissivity and 0.15% in the storativity. It is therefore clear tha the method of nonlinear regression analysis is superior to the conventional tangent construction method in pulse test analysis. This can be a consequence of the fact that the tangent method does not use all the data points as for the case of nonlinear regression method. Another interesting point in this example is the value of time lag at point C, $t_{\ell D2}$. Table 3 gives a value of $t_{\ell d2}$ of 0.415. The tangent at the curve in figure 6 passes at $t_{\ell d2} = 0.3$ and coincides with the pressure curve for a long time. The value of $t_{\ell do}$ is 0.2 from both Table 3 and the tangent in figure 16.

CONCLUSIONS

1- At low values of the dimensionless cycle period t_{cycD}, the pressure response curve does not exhibit peaks and valleys. An attempt to solve for three points with the same slope results in three coincident points with zero response amplitude. One should recognize and eliminate such points.

2- A single set of correlation curves of the dimensionless cycle period can be used for even and odd pulses. Even at pulse ratio R' are the same as odd at (1-R'). This behavior does not aply for the response amplitude.

3- The three time lags should be used in the correlations to check the reliability of the data. The three time lags are not equal even for equal pulse and shut-in periods.

4- Because of the graphical nature of pulse test analysis by the tangent construction method, this method is less accurate than analytical methods based on nonlinear regression.

NOMENCLATURE

B	= oil formation volume factor, RB/STB
E_i	= exponential integral function
h	= formation thickness, ft
K	= absolute permeability, md
n	= pulse number
P	= pressure, psi
P_D	= dimensionless pressure = $\frac{Kh\,\Delta p}{141.2\, q \mu B}$
P_{rD}	= dimensionless response amplitude = $\frac{Kh\,\Delta p}{70.6\, q\, B}$
q	= flow rate, STB/D
r	= distance between active and observation wells, ft
R'	= pulse ratio
S	= storativity = $h\, C_t$, ft/psi
t	= time, minutes
t_ℓ	= time lag, minutes
$t_{\ell D}$	= relative time lag = $t_\ell/\Delta t_{cyc}$
T	= transmissivity = Kh/μ, md.ft/cp
Δt_{cyc}	= cycle period, minutes
Δt_{cycD}	= dimensionless cycle period = $\frac{T\,\Delta t_{cyc}}{56900\, S\, r^2}$
μ	= viscosity, cp
ϕ	= porosity, fraction

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TABLE 1

RESULTS FOR N = 0 , R' = .1

TL1	DTCD	DPD	DTCD*TL1	DPD*TL1^2	TL0	TL2	INDX
0.05	11.8627	4.016E-01	0.5931	1.004E-03	0.0125	0.0142	0
0.10	6.8445	2.310E-01	0.6845	2.310E-03	0.0237	0.0270	0
0.15	4.7675	1.551E-01	0.7151	3.491E-03	0.0360	0.0410	0
0.20	3.5877	1.106E-01	0.7175	4.425E-03	0.0500	0.0567	0
0.25	2.8175	8.107E-02	0.7044	5.067E-03	0.0658	0.0743	0
0.30	2.2743	6.015E-02	0.6823	5.413E-03	0.0839	0.0937	0
0.35	1.8724	4.480E-02	0.6553	5.48[illegible]E-03	0.1042	0.1150	0
0.40	1.5650	3.333E-02	0.6260	5.3[illegible]3E-03	0.1269	0.1379	0
0.45	1.3246	2.469E-02	0.5961	4.999E-03	0.1519	0.1624	0
0.50	1.1336	1.817E-02	0.5668	4.543E-03	0.1793	0.1882	0
0.55	0.9799	1.328E-02	0.5389	4.017E-03	0.2095	0.2156	0
0.60	0.8546	9.618E-03	0.5127	3.463E-03	0.2431	0.2443	0
0.65	0.7515	6.903E-03	0.4885	2.916E-03	0.2804	0.2737	0
0.70	0.6657	4.896E-03	0.4660	2.399E-03	0.3221	0.3033	0
0.75	0.5938	3.427E-03	0.4453	1.928E-03	0.3684	0.3325	0
0.80	0.5328	2.358E-03	0.4262	1.509E-03	0.4196	0.3606	0
0.85	0.4804	1.586E-03	0.4084	1.146E-03	0.4764	0.3871	0
0.90	0.4353	1.038E-03	0.3918	8.404E-04	0.5392	0.4113	0
0.95	0.3960	6.529E-04	0.3762	5.892E-04	0.6086	0.4329	0
1.00	0.3615	3.903E-04	0.3615	3.903E-04	0.6852	0.4511	0

TABLE 2

RESULTS FOR N = 0 , R' = .5

TL1	DTCD	DPD	DTCD*TL1	DPD*TL1^2	TL0	TL2	INDX
0.05	6.3065	6.537E-01	0.3153	1.634E-03	0.0414	0.0563	0
0.10	3.5939	3.587E-01	0.3594	3.587E-03	0.0836	0.1141	0
0.15	2.5279	2.262E-01	0.3792	5.090E-03	0.1288	0.1708	0
0.20	1.9340	1.510E-01	0.3868	6.041E-03	0.1774	0.2250	0
0.25	1.5489	1.036E-01	0.3872	6.477E-03	0.2295	0.2763	0
0.30	1.2769	7.201E-02	0.3831	6.481E-03	0.2849	0.3245	0
0.35	1.0742	5.020E-02	0.3760	6.150E-03	0.3434	0.3695	0
0.40	0.9167	3.482E-02	0.3667	5.571E-03	0.4052	0.4115	0
0.45	0.7916	2.392E-02	0.3562	4.844E-03	0.4691	0.4501	0
0.50	0.6898	1.614E-02	0.3449	4.034E-03	0.5354	0.4853	0
0.55	0.6054	1.060E-02	0.3330	3.206E-03	0.6034	0.5167	0
0.60	0.5350	6.713E-03	0.3210	2.417E-03	0.6727	0.5436	0
0.65	0.4753	4.021E-03	0.3089	1.699E-03	0.7461	0.5653	0
0.70	0.4243	2.223E-03	0.2970	1.089E-03	0.8268	0.5807	0
0.75	0.3807	1.092E-03	0.2856	6.141E-04	0.9168	0.5880	0
0.80	0.3432	4.366E-04	0.2745	2.794E-04	1.0198	0.5842	0
0.85	0.3100	1.071E-04	0.2635	7.735E-05	1.1441	0.5618	0
0.90	0.2834	4.739E-06	0.2551	3.838E-06	1.2941	0.4985	0
0.95	0.3149	1.676E-08	0.2992	1.513E-08	1.4485	0.4782	0
1.00	0.2250	3.725E-09	0.2250	3.725E-09	1.4998	0.5000	0

TABLE 3

RESULTS FOR N = 0 , R' = .8

TL1	DTCD	DPD	DTCD*TL1	DPD*TL1^2	TL0	TL2	INDX
0.05	3.7130	2.717E-01	0.1856	6.793E-04	0.1081	0.2346	0
0.10	[illegible].2766	1.440E-01	0.2277	1.440E-03	0.2007	0.4153	0
0.15	[illegible].6483	8.441E-02	0.2472	1.899E-03	0.2986	0.5012	0
0.20	1.2805	5.059E-02	0.2561	2.027E-03	0.4029	0.5426	0
0.25	1.0333	3.017E-02	0.2583	1.886E-03	0.5131	0.5703	0
0.30	0.8530	1.735E-02	0.2559	1.561E-03	0.6282	0.5900	0
0.35	0.7169	9.469E-03	0.2509	1.160E-03	0.7436	0.6022	0
0.40	0.6110	4.759E-03	0.2444	7.614E-04	0.8562	0.6057	0
0.45	0.5261	2.050E-03	0.2368	4.152E-04	0.9637	0.5973	0
0.50	0.4559	6.121E-04	0.2280	1.530E-04	1.0752	0.5693	0
0.55	0.3998	5.735E-05	0.2199	1.735E-05	1.2098	0.5010	0
0.60	0.3796	6.109E-07	0.2278	2.199E-07	1.3013	0.4210	0
0.65	0.1734	2.328E-09	0.1127	9.837E-10	1.4500	0.4502	0
0.70	0.1105	3.492E-10	0.0774	1.711E-10	1.5000	0.5001	0
0.75	0.2654	1.863E-09	0.1990	1.048E-09	1.5499	0.550	0
0.80	1.0094	4.867E-03	0.8075	3.115E-03	0.5361	0.9711	0
0.85	0.1919	9.313E-10	0.1631	6.729E-10	1.6499	0.6501	0
0.90	0.1603	0.000E+00	0.1443	0.000E+00	1.6999	0.7000	0
0.95	0.1314	0.000E+00	0.1249	0.000E+00	1.7500	0.7500	0
1.00	0.1050	3.492E-10	0.1050	3.492E-10	1.8000	0.7999	0

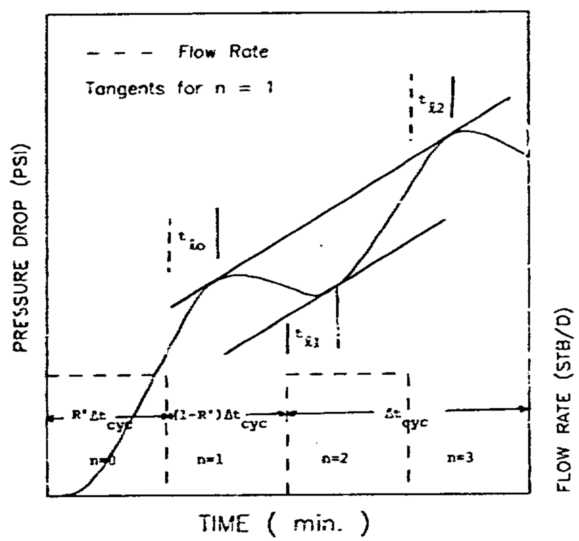

Fig. 1 – TERMINOLOGY FOR PULSE TEST ANALYSIS

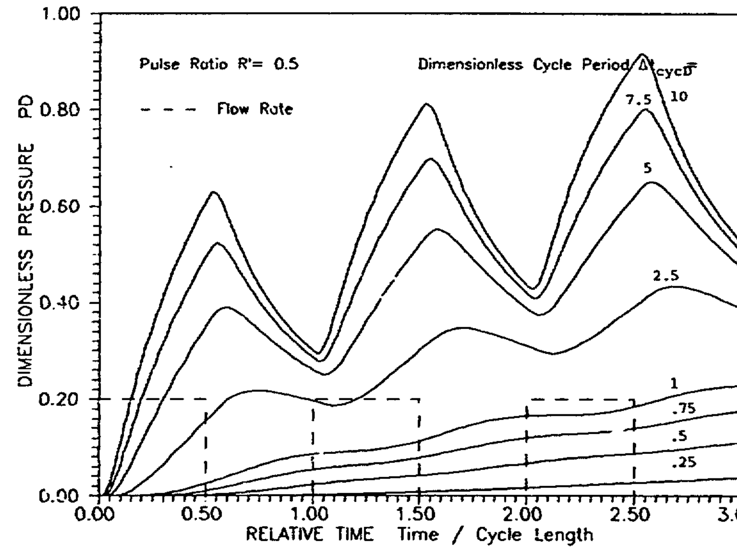

Fig. 2 – EFFECT OF DIMENSIONLESS CYCLE PERIOD ON PRESSURE RESPONSE

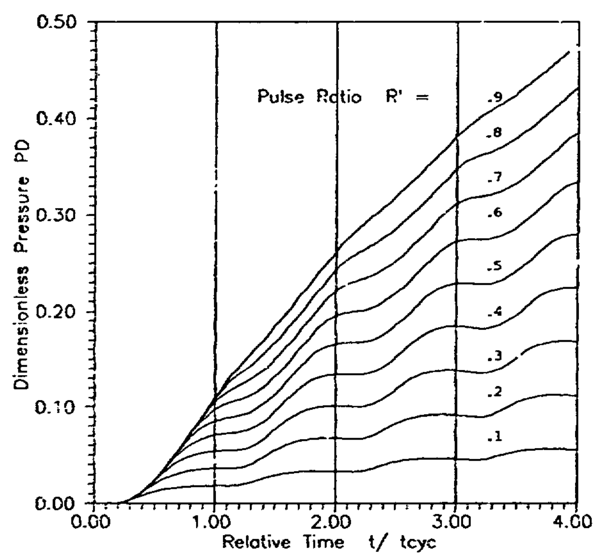

Fig. 3 – PRESSURE RESPONSE FOR tcycD = 1

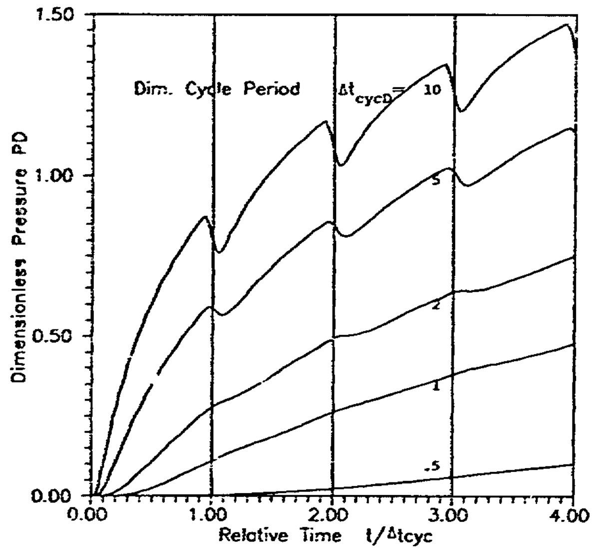

Fig. 4 – PRESSURE RESPONSE FOR R'=.9

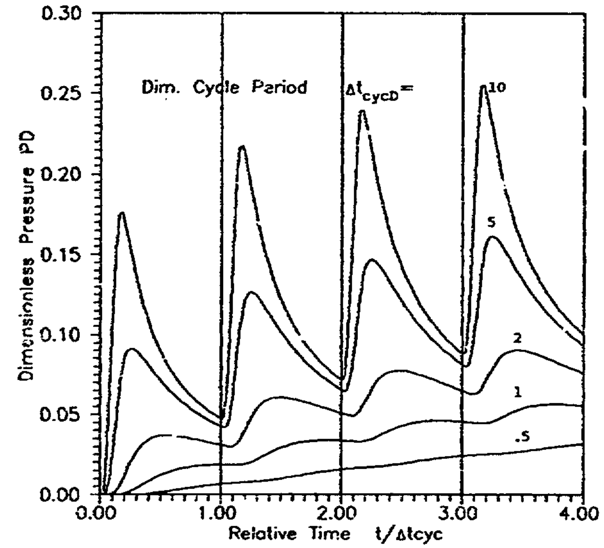

Fig. 5 – PRESSURE RESPONSE FOR R'=.1

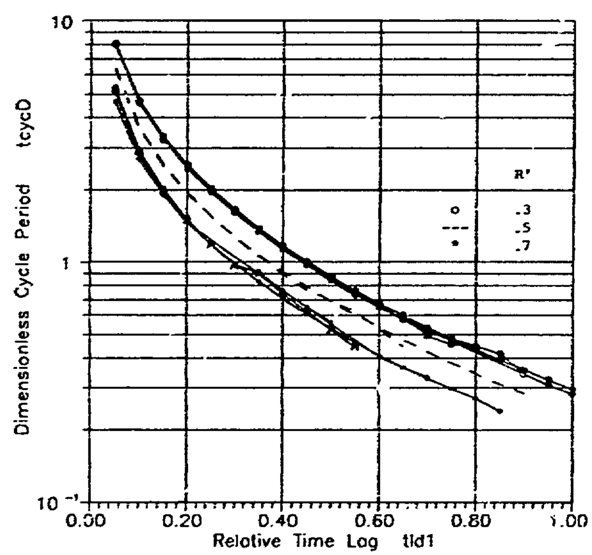

Fig. 6 – DIMENSIONLESS CYCLE PERIOD FOR EVEN AND ODD PULSES

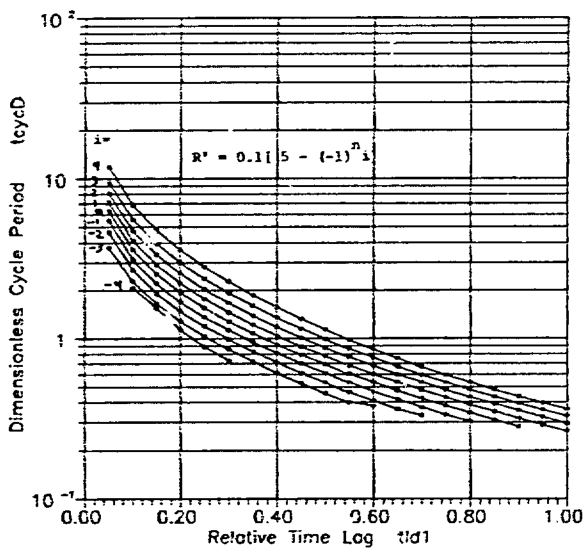

Fig. 7 – CORRELATIONS FOR DIMENSIONLESS CYCLE PERIOD

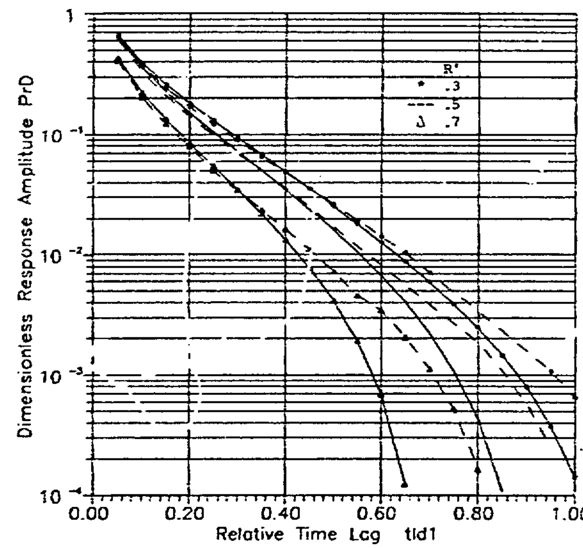

Fig. 8 – DIMENSIONLESS RESPONSE AMPLITUDE FOR EVEN PULSES

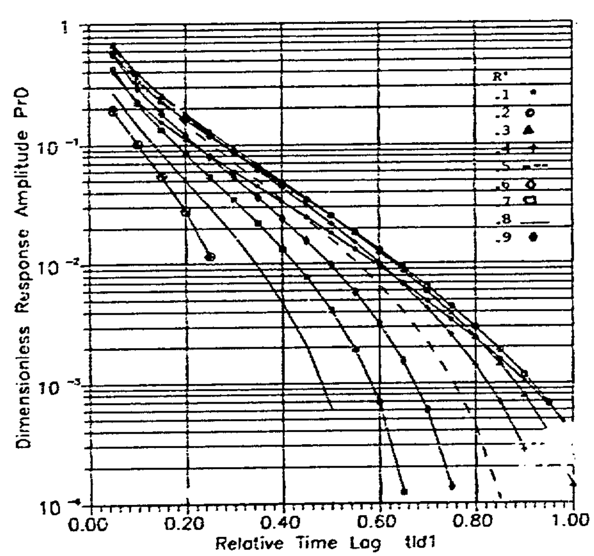

Fig. 9 – CORRELATIONS FOR DIMENSIONLESS RESPONSE AMPLITUDE FOR $n = 0$

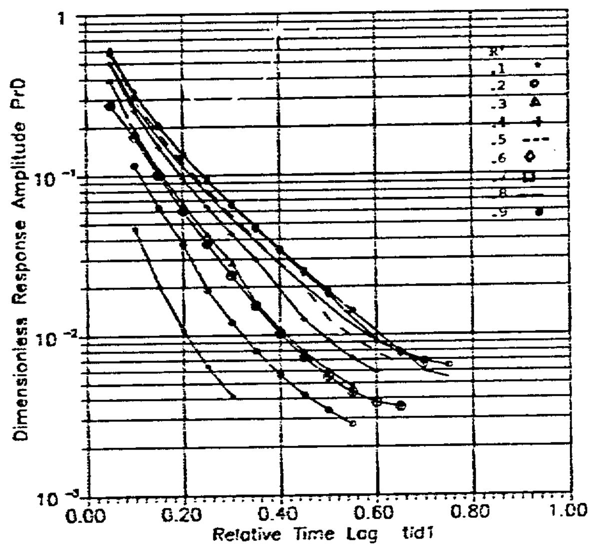

Fig. 10– CORRELATIONS FOR DIMENSIONLESS RESPONSE AMPLITUDE FOR n = 1

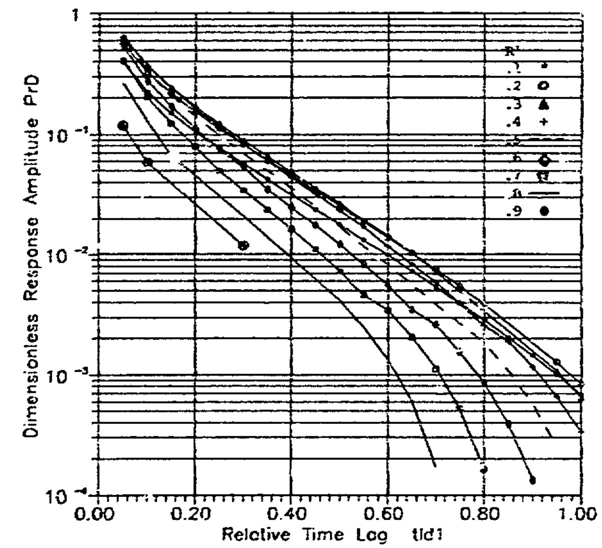

Fig. 11– CORRELATIONS FOR DIMENSIONLESS RESPONSE AMPLITUDE FOR n = 2

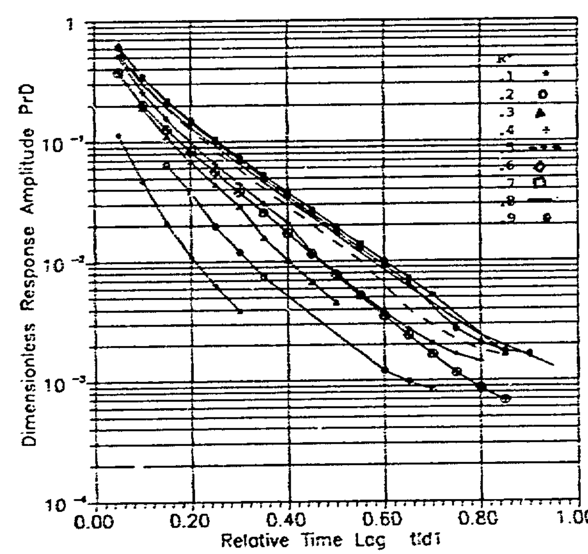

Fig. 12– CORRELATIONS FOR DIMENSIONLESS RESPONSE AMPLITUDE FOR n = 3

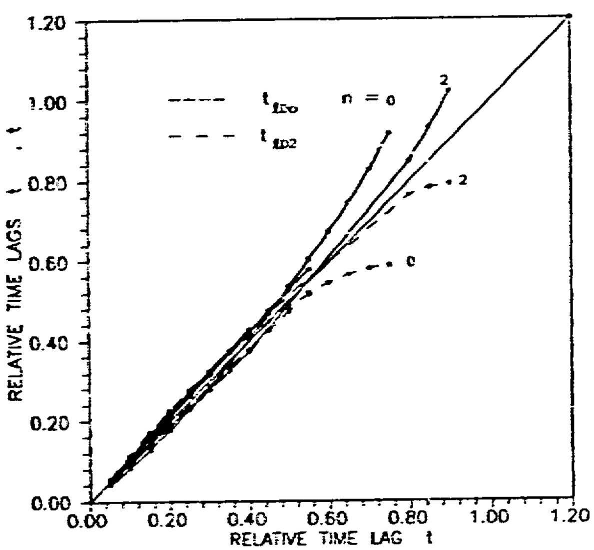

Fig. 13 – CORRELATION OF THE THREE TIME LAGS AT R'=.5

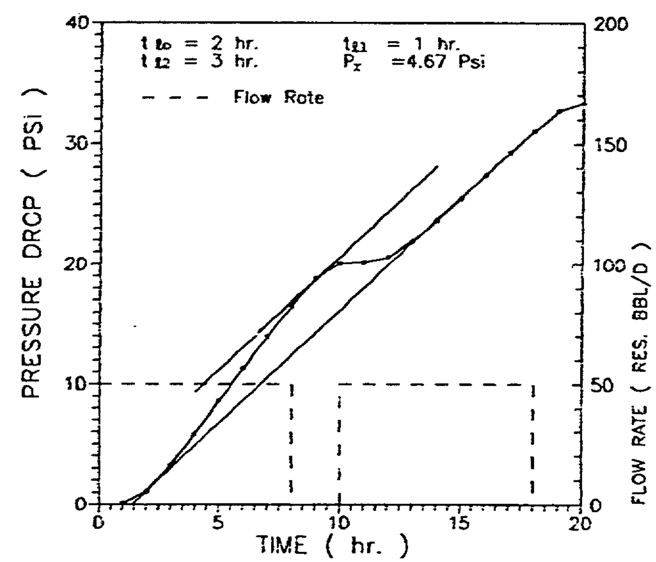

Fig. 14 – EXAMPLE OF PULSE TEST ANALYSIS